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Battlescale Forecast Model (BFM) Target Area Wind Speed Validation Over WSMR, NM Initial Results

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Preface

This report describes forecast target area wind speed validation results derived from the U.S. Army's Battlescale Forecast Model (BFM). Forecast output was produced using archived weather balloon data collected during November and December 1974 at White Sands Missile Range, NM.

The BFM has been integrated into the prototype Meteorological Measuring Set-Profiler system developed by the U.S. Army Research Laboratory to produce 4-D meteorological forecast fields to be used by artillery soldiers in the battlefield.

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Executive Summary

Target area artillery wind speed forecasts derived from Battlescale Forecast Model (BFM) output have been validated using upper-air weather balloon data from a 1974 network of launches over White Sands Missile Range (WSMR), NM. BFM forecasts were produced on a 200 MHz Pentium personal computer (PC). Raw balloon data used in the study were from the network of nine stations scattered across the range. Target area validation data came from the two northernmost stations at the Apache and Holloman, NM locations. The BFM was run using different combinations of the seven southern range stations that supplied initialization data for the model. The BFM was allowed to "spin up" to produce 0-h nowcast wind prediction fields at the target locations based on the different initialization data combinations from the other seven stations.

Gridded BFM output at the targets was converted to standard artillery computer meteorological messages consisting of ten levels of wind data from the surface to 4 km above ground level (AGL). Output from these BFM messages was compared against similar messages derived from balloon launches at the targets and treated as "truth." Additionally, BFM output was compared against messages produced by the default met and time space weighted (TSW) model techniques for the same cases. Statistical validation calculations show that the BFM performed 75 percent better than the default met technique and 21 percent better than the TSW model technique.

1. Introduction

Meteorological conditions directly impact a projectile's or rocket's launch-to-land route of flight. Additionally, other factors such as muzzle velocity and muzzle temperature, aiming, and numerous other variables associated with firing the munition toward the target affect the trajectory. However, variations in atmospheric density, temperature, wind speed and direction are the most sensitive and critical factors that may cause the munition to miss its intended target, assuming the muzzle was properly aimed. Ignoring weather impacts in artillery aiming calculations can account for nearly 50 percent of the bias error for projectile targeting and nearly 95 percent of the bias error for rocket targeting. [1] Clearly, providing accurate meteorological data for artillery targeting algorithms can dramatically improve the chances for first-round fire success. As artillery modernization continues into the future, more dependence will be placed on improving first-round fire for effect from unguided cannon rounds, as well as precision-guided munitions and submunitions that will "lock on" to their targets for final aiming corrections after they are launched. The demand for accurate target area meteorological forecasts will increase in support of these munitions, especially considering plans to extend their gun-to-target ranges to at least 200 km. This report summarizes the initial accuracy results of target area wind speed forecasts produced by the Battlescale Forecast Model (BFM) supporting artillery missions.

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2. Current Artillery Meteorology Capabilities

Deployed artillery units rely on meteorological data supplied by weather balloons launched within a few kilometers of the gun location. Upper-air data supplied by these balloons are converted into an alphanumeric fire control computer met message (MET-CM) that covers 26 "lines" or vertical zones of meteorological data from the surface to 20 km above ground level (AGL). Each line contains mean zone wind direction, wind speed, virtual temperature, and pressure data used by the fire control computers in artillery aiming algorithms. The upper-air data is assumed to accurately depict the vertical profile of meteorological parameters over the apogee point of the projectile's trajectory. Problems with this assumption include the following:

- For a launch site at least 20 to 30 km away from the target, the apogee location may actually be located in a completely different microclimate, such as on the opposite side of a hill or mountain, in a river valley, etc. Data collected by the balloon may not accurately reflect true data at the apogee or at the target location.

- The balloon data could be "time stale" or more than 1-hour old. This is an important concern when temperature inversions are present (dawn/dusk, high pressure regimes, etc.) or frontal boundaries, jet streaks, and other phenomena are causing significant changes in the local wind and temperature patterns across space and time.

- The balloon data could be "space stale," meaning that the balloon could drift far from the intended apogee point during the course of its flight.

- Artillery meteorology (ArtyMet) units do not exchange meteorological data; thus, a more recent balloon launch a short distance away from an artillery battery may be ignored and stale data used instead.

- In the complete absence of balloon data, "default met" or standard atmosphere curves of temperature and dew point are used and wind speed/direction is assumed to be zero everywhere. This is the worst case scenario and is the cause for the most serious artillery aiming errors.

Improvements to the current ArtyMet capabilities are being implemented. The time space weighted (TSW) model will be included as part of a hardware/software upgrade for ArtyMet equipment. [2] Artillery units will be

able to exchange local balloon data with other ArtyMet units deployed in their immediate area. Thus, data from up to three recent weather balloons from different locations will be used to generate the MET-CM. TSW utilizes all recent available ArtyMet balloon data, weighs the data temporally and spatially in an objective analysis to produce a vertical profile, and allows for "stale" data up to 4-h old to be included with more recent and current data. The main problem with TSW is that even though more current and accurate data may be collected for generating the MET-CM, the data is still only collected from a few localized ArtyMet locations, with data again "assumed" to be valid far away at the apogee of the trajectory and over the target area. Additionally, TSW does not consider terrain and local diurnal heating/cooling effects on the objectively analyzed meteorological parameters.

Although TSW provides significant improvement over single-station data, and dramatic improvement over default standard atmosphere data, there is still a very important need for improving meteorological data for aiming algorithms at the apogee location, over the target area, and along the entire trajectory of the shell. Future weapon systems will also require data for trajectories and targets up to hundreds of kilometers away from the launch location. Wind speed/direction, virtual temperature, and density/pressure calculations along the trajectory will still be required. Additionally, advances in projectile munition and submunition sensitivities and target acquisition needs lead to the requirement for forecasting such parameters as clouds, precipitation, visibility, icing, turbulence, and severe weather over the target area. To meet these long-range targeting sensitivity requirements, four-dimensional gridded mesoscale model forecast output will supply ArtyMet units and fire control algorithms with onsite and realtime launch, trajectory, and target area weather data. The BFM is the first model being tested to meet these needs.

3. Mesoscale Modeling on a PC

To meet the near-term needs of the U.S. Army's ArtyMet soldiers, the mesoscale model of choice has to run on Army common hardware. For ArtyMet hardware, this will be the Pentium personal computer (PC) platform. The goal is to be able to host a mesoscale model on the PC that can produce realtime nowcasts over horizontal areas as large as 250 x 250 km. The first version of the BFM is driven by the hydrostatic Higher Order Turbulence Model for Atmospheric Circulations (HOTMAC). [3] As PC hardware and software evolve in the future, a major goal is to transition to a more sophisticated hydrostatic or nonhydrostatic model.

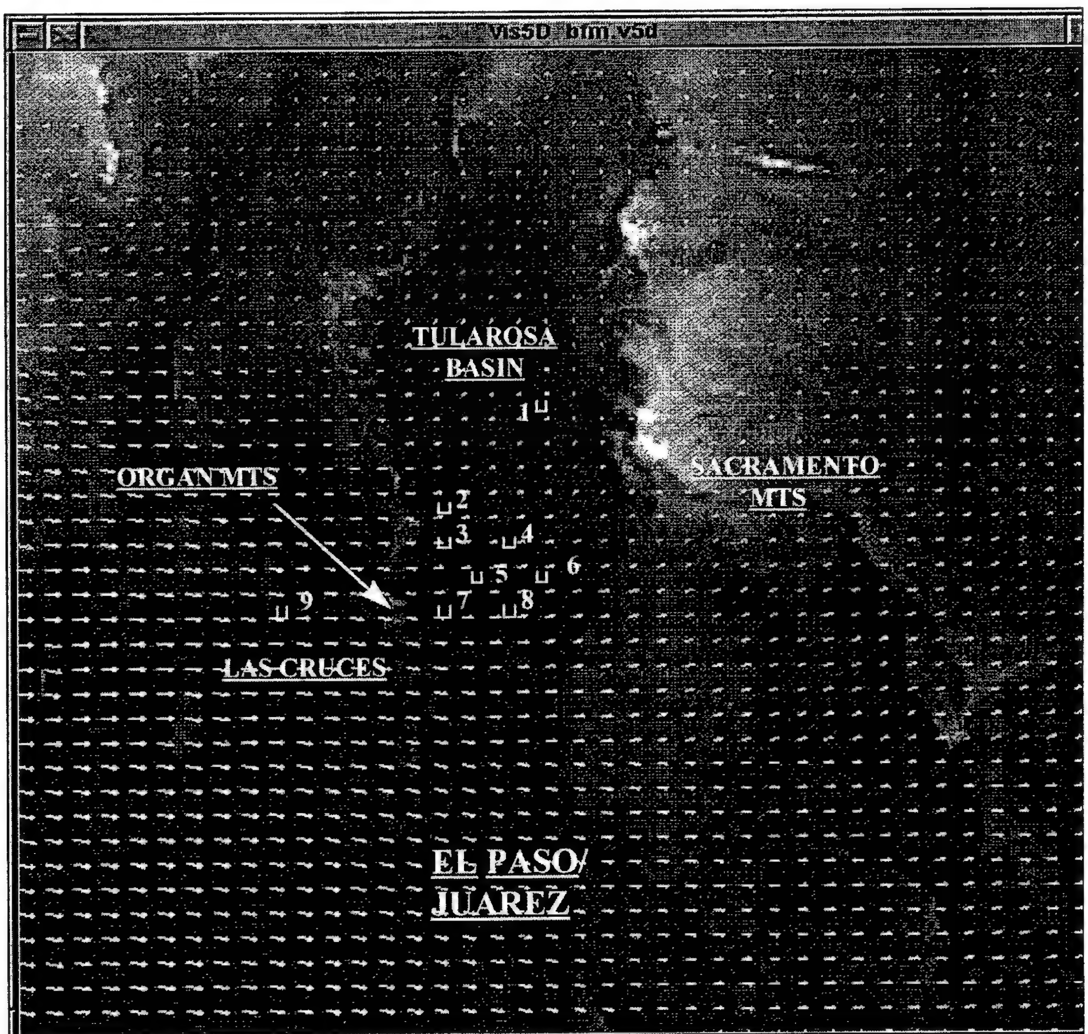
The HOTMAC-driven BFM is a boundary layer model that has been tailored to meet the U.S. Army's specialized battlefield needs. Model physics include latitudinal, seasonal (including effects of slope on incoming solar radiation), and diurnal radiation effects, a dynamic boundary layer, and land/water contrasts. For this study, it was run on the PC with 32 vertical levels from the surface to 12 km mean sea level (MSL). Horizontal resolution was 8 km across the domain. PC hardware requirements for running the BFM include a Pentium 200 MHz system with 128 MB of RAM and one 2-GB hard drive. The BFM took approximately 5 min/h of model output to run, with the same time ratio applied to the 15 min of model spin-up time (3 model h) necessary to start producing forecast data.

The BFM can be run in two modes of operation. The full mode includes initializing the model with all available raw data recently received from the model domain area of coverage, plus supplemental upper-air data from the domain's boundary area. Additionally, the full mode includes regional model initialization grids for BFM "steering" toward the desired forecast hour solution, allowing the BFM to produce forecasts out to 12 h and beyond. In degraded mode, the BFM can be run without the benefit of regional model steering grids, but model forecast output is restricted to a maximum of 6 h.

4. Conclusions

BFM validation has been completed for wind speed forecasts over White Sands Missile Range (WSMR), NM. The BFM was run in degraded mode, initialized only with archived surface and upper-air data from the Prototype (Meteorological) Artillery Subsystem (PASS) database from 1974. [4] For this experiment, nine upper air data locations were set up in and around the WSMR, NM, area. These data sets were collected at varying hours from dawn to dusk on each test day and provide an excellent source of information for evaluating target area forecasts without the benefit of large-scale model initialization feeding the BFM.

The figure depicts a sample wind field for the WSMR area of interest and the upper-air stations used in the study. The two northernmost stations, Holloman (1) and Apache (2), were treated as the "targets" or BFM forecast locations.



PASS database topographical depiction with locations of upper-air data sites.

In the figure, brighter terrain depiction corresponds to higher elevations. BFM 0-h output at 1700 Universal Time Coordinates (UTC), 2 December 1974, is presented. Wind vectors shown are at 3 km MSL at each model grid point (8-km horizontal resolution). Holloman (1) and Apache (2) are the target locations used to validate BFM output. The distance from Las Cruces (9) to Holloman is 100 km.

4.1 Validation Procedures

Validation was accomplished for wind speeds at the lowest ten MET-CM levels from the surface to 3500 m AGL. Varied 3-station TSW combinations of southern WSMR upper-air stations were used to initialize the BFM (hereafter referred to as the "3-station BFM") for 0-h model output verification at Holloman and Apache. The TSW upper-air data consisted of radiosonde observations (RAOB) from three locations for each case: (1) RAOB location being current (0-hr), (2) 2-h old RAOB, and (3) 4-h old RAOB. Three types of target area forecasts valid at Holloman and Apache were compared for each case: default met (zero winds), the 3-station TSW technique, and the 3-station BFM. Additional BFM degraded runs were accomplished using 0-h upper-air data from all seven initialization stations (7-station BFM). Default met, TSW, and BFM output were transposed into MET-CMs valid at Holloman and Apache. Validating upper-air data from the target locations were also transposed to the MET-CM format so comparisons could be completed.

4.2 Validation Results

Results of all comparisons are shown in table 1. Data shown represents 52 cases for the BFM runs using all seven stations and for the default met cases. For the TSW and 3-station BFM runs, 32 cases were studied. Root mean square error (RMSE) and mean absolute error (MAE) statistics show the significant improvement of TSW over default met. More importantly, comparisons of TSW against the 3-station BFM show the BFM improving upon TSW by 8 to 10 percent. Also, the 3-station BFM shows a 75 percent improvement over default met. The 7-station BFM improvements range from 20 to 22 percent better than TSW.

Table 1. RMSE and MAE verification statistics for PASS cases validated at the Holloman and Apache locations

	Default met	3-station TSW	3-station BFM 0-hr	7-station BFM 0-hr
RMSE (kts)	17.71	4.99	4.58	4.00
MAE (kts)	13.82	3.70	3.33	2.88

Note: data shown includes calculations for all ten MET-CM levels.

More detailed comparisons of MAE and bias (average forecast speed - average observed speed) between TSW and the 3-station BFM output by the MET-CM level are shown in tables 2 and 3, identified by verification location. Some of the more interesting results show that the combined MAE statistics for the BFM outperform TSW except at the surface and at the highest verified level. Bias statistics show the BFM underforecasting wind speeds near the surface, especially at the Apache site. The large low-level MAE at Apache and corresponding negative bias values can be linked to the BFM's tendency of delaying the mixing of higher wind speeds aloft to the surface layer as daylight hours progress and diurnal heating occurs.

Since this study has been completed, modifications to the BFM's use of raw surface data have been implemented which should eliminate these low-level problems. Breaking out the surface and 100 m AGL statistics by location, TSW was better at the Apache site, yet the BFM was better at Holloman, further away from the initializing stations used. This comparison shows the utility of using a mesoscale model for depicting boundary layer conditions far from the areas where raw initializing data were collected. Aloft, bias statistics show the BFM outperfoming TSW forecasts with the BFM only slightly underforecasting speeds at the highest levels studied at Apache. Though MAE statistics show the BFM was the better model at the Apache site, TSW was better at Holloman at levels 2250, 3250, and 3750 m AGL. These errors aloft would be reduced or eliminated if the BFM could have been run in full mode using regional model initialization gridded data. Also, the longer range uses of the BFM for target area conditions more than 50 km away from the raw data input locations would be expected to show the BFM outperforming the TSW.

Table 2. MAE (kts) statistics by vertical levels comparing the TSW model with the 3-station BFM output at each verification location and combined

Level (m AGL)	Holloman TSW	Holloman BFM	Apache TSW	Apache BFM	Combined TSW	Combined BFM
Surface	3.03	2.87	3.86	4.07	3.43	3.45
100	4.65	3.16	3.00	3.48	3.85	3.32
350	3.55	3.29	3.35	2.83	3.45	3.07
750	3.39	3.32	3.48	2.62	3.43	2.98
1250	5.29	4.16	3.83	2.93	4.58	3.57
1750	4.68	4.00	4.00	3.10	4.35	3.57
2250	2.74	2.94	3.55	3.28	3.13	3.10
2750	3.87	3.23	4.17	3.38	4.02	3.30
3250	2.52	2.87	3.59	3.21	3.03	3.03
3750	3.55	4.06	3.86	3.79	3.70	3.93
All Levels	3.73	3.39	3.67	3.27	3.70	3.33

Table 3. MAE (kts) statistics by vertical levels comparing the TSW model with the 3-station BFM output at each verification location and combined, for bias (kts) statistics

Level (m AGL)	Holloman TSW	Holloman BFM	Apache TSW	Apache BFM	Combined TSW	Combined BFM
Surface	-0.77	-0.03	-3.17	-3.45	-1.93	-1.68
100	3.03	0.77	0.93	-2.38	2.02	-0.75
350	2.58	1.42	1.34	-0.55	1.98	0.47
750	2.29	1.71	1.90	0.76	2.10	1.25
1250	4.52	3.06	1.83	-0.24	3.22	1.47
1750	3.58	2.77	1.45	0.14	2.55	1.50
2250	2.48	1.52	2.79	1.21	2.63	1.37
2750	2.45	0.97	3.48	1.38	2.95	1.17
3250	1.68	1.06	2.21	0.59	1.93	0.83
3750	1.74	0.77	1.59	-0.41	1.67	0.20
All Levels	2.36	1.40	1.43	-0.30	1.91	0.58

5. Recommendations

The BFM provides improved target area wind speed forecast accuracy over the TSW model output as shown in this initial verification study. Cases studied using the PASS database over WSMR show decreased errors in wind speeds from the surface to 4 km AGL in BFM output compared to TSW and default met output. Site validation statistics at Holloman and Apache revealed certain model weaknesses in depicting surface wind speeds at Apache and upper-level speeds at Holloman. However, adjustments to the model and improved initializing databases in the future will reduce or eliminate these small errors. Even without these BFM adjustments, overall statistics showed significant improvement in BFM target area wind speed depictions over the current 3-station TSW and default met techniques.

Future work and technical reports will compare these same BFM wind forecasts to each single TSW sounding to produce BFM results compared against persistence. Also, validation statistics will be calculated and similarly reported for virtual temperature, pressure/height, and wind direction accuracy from the surface to 4 km AGL. Initial results prove the BFM will provide ArtyMet soldiers with much needed accuracy and timeliness for future implementation of precision-guided munitions requiring meteorological data forecast over the target area.

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Acronyms and Abbreviations

AGL	above ground level
ARL	U.S. Army Research Laboratory
ArtyMet	artillery meteorology
BFM	Battlescale Forecast Model
HOTMAC	Higher Order Turbulence Model for Atmospheric Circulations
MAE	mean absolute error
MET-CM	fire control computer met message
MSL	mean sea level
PASS	Prototype Artillery Subsystem
PC	personal computer
RAOB	radiosonde observation
RMSE	root means square error
TSW	time space weighted
UTC	Universal Time Coordinates
WSMR	White Sands Missile Range

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